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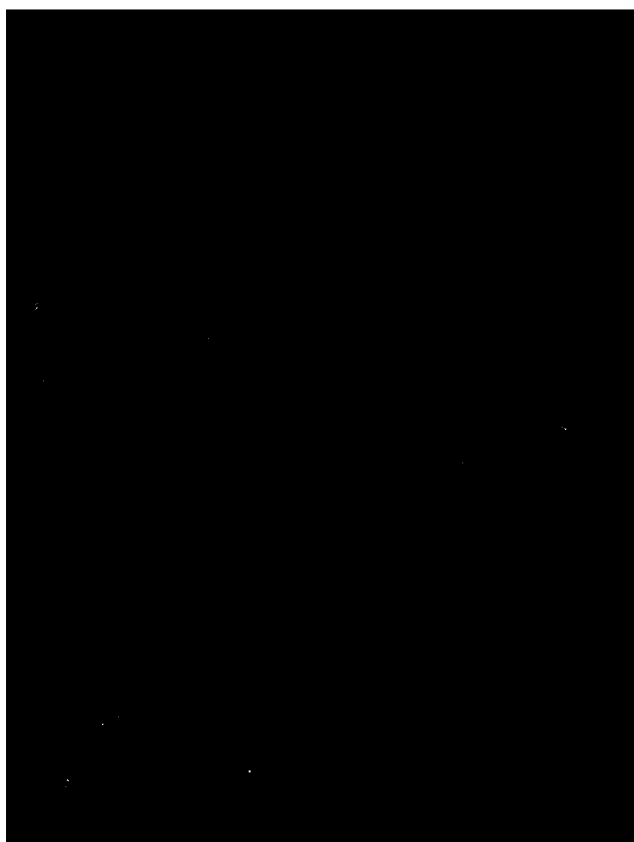   SEP 80 W L WOOD   N00014-75-C-0716
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Final Report. May 75 - Sep 80,

APPLICATION OF SHORT-CRESTED WAVE THEORY
IN THE DESIGN OF THREE DIMENSIONAL
COASTAL HYDRODYNAMIC MODELS.

William L. Wood

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September 1980

INTRODUCTION

In spring 1973 a series of field experiments was
initiated to investigate the three dimensional structure of
a coastal hydrodynamic system. Specific emphasis was placed
on those components of the system which were driven primarily
by incident wind-waves. These field investigations supported
the concept that short-crested wave theory is applicable
to modeling of incident wind-wave transformations from
offshore to the outer surf zone. Application of short-crested
wave theory to the design of coastal hydrodynamic models was
also considered appropriate because of the theories inherent
three dimensional structure. Concurrent with this work two
field experiments were conducted in 1974 and 1976 to measure
longshore current velocity structure. These experiments
were designed to measure vertical and horizontal distribution
of current velocity and to monitor temporal variations in
current velocity at a point. In fall 1978 a series of exper-
imental laboratory investigations was initiated to make
precise measurements, at close spatial intervals, of wave
height decay after breaking. These experiments were carried
out to determine a wave height decay expression based upon
the assumption that an appropriate physical conceptualization
of wave energy dissipation after breaking must consider
turbulence dominant to bottom friction. This report presents
a detailed summary of these investigations and their results.

During the project period of this contract five professional papers, five Technical Reports, and eight papers for presentation at national meetings have been prepared. A complete listing of these reports and papers is appended to this report.

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SHORT-CRESTED WAVES AT A COAST

The common occurrence of short-crested waves in open
ocean and over the continental shelf suggests that these
waves must have significant influence on coastal wave distri-
bution. A preliminary evaluation of coastal aerial photographs
and satellite imagery from regions of the Atlantic and Pacific
coasts of North America indicate that short-crested wave
fields are common in offshore areas and that they usually
persist to the outer surf zone. McClenan and Harris (1975)
in a study on the use of aerial photography for determining
wave characteristics concluded that two to five directionally
distinct wave trains were present in most offshore regions.
Photographs at Cape Hatterus, North Carolina, Cape Canaveral,
Florida, Point Reyes, California, and various locations along
Lake Michigan also show that short-crested waves are commonly
present at the outer surf zone.

This common occurrence of short-crested waves at a coast
stimulated initial interest in research on short-crested
wave theory applied to coastal hydrodynamic modeling and in
conducting field experiments to verify modeling results.
In fall 1974 a three by three grid of wave staffs was placed
in the surf zone to measure wave height variability along-the-
crest of transforming, breaking waves. Results from these
short-crested wave transformation experiments showed crest-
wise variability in wave height to be present at the outer

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surf zone. Statistical analysis of these along-the-crest
wave height variations indicated significant differences
in their probability distributions. The spatial scale of
this along-the-crest variability was of the order of normal
incident wave length. A discussion of these results was
published in the Proceedings 15th International Conference
on Coastal Engineering (Wood, 1976).

Four mechanisms have been evaluated as possible causations
of non-uniformity along-the-crest of waves incident at the
outer surf zone. These mechanisms are: significant long-
shore variation in bottom geometry; interaction of long-
crested swell arriving from two distinct directions; interaction
of edge waves with the incident wave field; and arrival of a
"short-crested" wave field generated by local storm winds.
Of these four mechanisms surf zone bottom geometry was shown
to have little influence on short-crested wave structure
(Wood, 1976).

Interaction of long-crested swell arriving from two or
more distinct directions is clearly an important mechanism in
the generation of non-uniform wave crests and has been dis-
cussed by Longuet-Higgins (1956), McCleanan and Harris (1975)
and Dalrymple (1975). Qualitatively, it would be expected
that waves of the same wave number, approaching from different
directions, would be refracted so that their crests are more
nearly parallel to each other and to the coast. For small
differences in wave angle of approach ($\delta\theta \sim 10^{\circ}-20^{\circ}$) the
deviation of wave components is greatly reduced and the

resulting incident wave field tends to become long-crested.
For large differences in wave angle of approach ($\delta\theta \sim 60^{\circ}\text{-}90^{\circ}$)
the deviation of wave components is far less effected and
the wave field remains short-crested. If wave angle of
approach (θ) is held constant, but a spectrum of wave numbers
is considered the expectation is that individual wave numbers
will be differentially refracted. This will increase the
angular deviation of individual components and produce a
short-crested wave field. A broad wave number spectrum will
produce an extremely short-crested wave field.

Edge wave interaction with the incident wave field is
possible. Fluctuations in longshore velocity with a period-
icity close to that of a zero mode edge wave have been observed
under field conditions (Wood and Meadows, 1975; Meadows, 1976).
However, the wave length of longshore wave height fluctuations,
from this experiment, are equivalent to the incident wave
length of breaking waves. Periodicity of these fluctuations
is much shorter than those calculated from edge wave theory.
Likewise the observed magnitude of wave height fluctuations
is in excess of that calculated from edge wave theory.

An incident wave field arriving with a "short-crested"
structure which is independent of the other three mechanisms,
is theoretically possible but, within the limitations of
existing experimental observations difficult to substantiate.
Turbulence in a wind field can result in the generation of
a short-crested wave field (Jefferies, 1924). Likewise
McClenan and Harris (1975) analyzed 40,000 aerial photographs

of waves in shallow-water and concluded that the dominant
pattern is one of short-crested waves and randomness.
Notably missing between these studies are concurrent obser-
vations of wind and wave field structure in shallow-water.
The crest-wise wave length correspondence to incident breaking
wave length and the large fluctuations in wave height along-
the-crest do, however, strongly support short-crested wave
structure. Clearly, the question left unanswered is whether
energy is being transmitted along the crests of these waves.
In order to address this question affectively it is necessary
to understand internal dynamics in the upper half of trans-
forming and breaking shallow-water waves.

Since experimental evidence supported the contention
that short-crested waves were an anticipated form of incident
waves at a coast, a theoretical evaluation of three-dimensional
surf zone motions was initiated. Two distinct causes of long-
shore variation in surf zone motions were initially investi-
gated: variations in longshore bottom geometry and longshore
incident wave height variability. In a paper "Dependency of
Surf Zone Motions on Longshore Bottom and Wave Variability"
Wood (1976) presented a first attempt at a linearized solution
to the three-dimensional equations of motion using variable
non-dimensional bottom and wave height parameters. That
paper presented the following results.

Let ε and B be two small parameters characterizing
normal and longshore bottom slope respectively. The ratio

of these two parameters has two value ranges which are
of interest:

$B/\varepsilon \simeq 1$ and $B/\varepsilon \rightarrow 0$. If $\varepsilon \rightarrow 0$
momentum transport parallel to shore dominates shoreward
normal transport. However, when $B/\varepsilon \rightarrow 0$ with $B<<\varepsilon$ and
longshore currents are still observed, then longshore wave
variability must be considered as an important driving
mechanism.

A linearized solution to the three dimensional equations
of motion was obtained under the assumptions of $B/\varepsilon \rightarrow 0$
and $\partial/\partial y \neq 0$. The resulting hyperbolic equation could be
transformed to a wave equation with coordinates oblique to
the surf zone. The solution of this equation was complex
but, the form of the equation suggested three possible physical
interpretations: first a solution may exist with a velocity
potential which is dependent upon a cos mx cos ny form, where
m and n are onshore and longshore wave number respectively;
second along-crest variations in wave height may serve as a
momentum transfer mechanism in the surf zone; third an inter-
action of longshore stresses with crest normal stresses may
provide a longshore forcing function in three-dimensional
space. These results were far from complete, yet even in
their preliminary form they opened up an area of theoretical
endeavour which needed further development.

An evaluation of momentum balance related to non-uniform
wave height distributions along the crest of breaking waves
was subsequently completed, producing two interesting results.

First it showed that the principal radiation stress <u>parallel</u> to the wave crest is <u>underestimated</u>. This underestimation occurs from the physical neglect of the ρV^2 term in the gradient of the dynamic pressure. Second the various long-shore gradients in the momentum balance expressions which had been ignored by previous investigators, appear to contribute to the momentum balance in a non-negligible way. These two results are additions to the original recognition by Battjes (1972) of the <u>overestimation</u> in the principal radiation stress <u>normal</u> to the wave crest under non-uniform conditions.

Short-crested wave refraction modeling was initiated utilizing narrow-band spectra of wave angles and wave numbers. Initial formulation followed the basic line of reasoning put forth by Longuet-Higgins (1956, 1957). However, Longuet-Higgins (1956) did not attempt to extend his formulation of the wave refraction problem, into shallow water ($d/\lambda < 0.05$). Furthermore, he noted that the linear treatment utilized in his 1956 work was totally unacceptable near and within the surf zone.

Initial tests of this linear short-crested wave refraction model yielded results which agree physically with those results suggested by Longuet-Higgins (1956). Specifically, the mean crest-length of short-crested waves refracting in shallow water may either increase or decrease. Likewise, the ratio of crest length to wave length, in general, tends to increase as waves pass over a gradually shoaling, plane, shallow water bathymetry.

This model is limited by the conventional constraints of small-amplitude wave theory. This dispersive type of refraction, which is dependent upon wave number and depth, is not appropriate to shallow-water regions adjacent to and within the surf zone. Therefore, an amplitude dependent dispersive type wave refraction approach was introduced into the model.

This new modeling approach utilized a modified form of solitary wave theory in and near the surf zone. The introduction of solitary wave theory, to the model, would have little effect on wave refraction as long as a uniform long-crested wave field was used as input. However, for incident waves with non-uniform crests, a pronounced differential refraction occurs as a direct function of wave height. An incident short-crested wave field refracts much more rapidly than a long-crested wave field because of the height dependency of the celerity field. The amount of refraction is governed by the ratio of successive differences in along-the-crest wave height to crest-wise wave length. As this ratio increases, the wave angle spectrum broadens. For a set of initial conditions, where a continuous straight non-uniform wave crest is imposed at the outer limits of a gradually shoaling plane bottom, differential refraction will create a surface wave pattern characterized by angular discontinuities. This pattern is strikingly similar to patterns observed in aerial photographs of short-crested waves in shallow water.

This work on short-crested waves has broadened our understanding of three-dimensional surf zone dynamics. It has contributed to physical conceptualization of longshore forcing which can be as important as any of the other proposed forcing mechanisms. Modeling of three-dimensional surf zone motions utilizing short-crested wave theory has not been as successful as was originally anticipated because of complexities in solving the necessary mathematical expressions. Qualitative results have been encouraging, but quantitative solutions have not been achieved.

Recently, some effort has been directed towards understanding transformations of wind generated short-crested sea surfaces as they move from deep to shallow-water. Wood (1980) showed that the characteristic along-the-crest wave length at a coast for a transformed short-crested sea surface is equivalent to the deep water wave length of that system. This result is interesting because the calculated longshore periodicity of these short-crested transformed sea surfaces is close to that of observed long period variations in longshore currents (Wood and Meadows, 1975; Meadows, 1976; Meadows, 1978; Meadows and Wood, in press).

LONGSHORE CURRENTS

In two nearly simultaneous studies Dette, 1974 and
Wood and Meadows, 1975 observed that velocity fluctuations
in longshore currents on the order of 150% of mean velocity
occurred on time intervals from three to eighty seconds.
Since that time extensive analysis has been carried out in
order to resolve spatial and temporal structure in longshore
currents. The following discussion is designed to summarize
this analysis. Detailed discussion is omitted when it
exists in other published forms.

Three distinct longshore current velocity components
have been isolated, which contribute to the total observed
longshore current velocity

$$V = \bar{V} + V'_W + V'_L$$

where $\bar{V}$ is the steady component, V'_W is a fluctuating component
with a periodicity of the incident breakers, and V'_L is a
long-period fluctuating component. The mean longshore
component $\bar{V}$, has been found to be dominated by the combined
fluctuating components. The high frequency unsteady component
corresponds to the incident wave horizontal particle velocity
resolved alongshore. Resolution of the long-period component
is not as simple.

Long-period variations in longshore current velocity have
been observed by numerous investigators (Inman and Quinn, 1951;
Sonu, 1972; Huntley and Bowen, 1974; Suhayda, 1974; Wood and

Meadows, 1975; and Meadows, 1977) and have been shown to be an important component of nearshore dynamics (Bowen and Inman, 1971; Waddell, 1973; Suhayda, 1974; Meadows, 1977). However, with all of these studies the mechanism responsible for and general form of long-period waves in the surf zone has not been well established.

Analysis of phase relations between sequential 1000 second time series records of the free surface show that both standing and progressive long-period waves are present in the surf zone at the same time. Previous studies have related surf zone circulation to one or the other of these two modes, but have not recognized their coexistence. Physically, it is quite reasonable to expect both wave modes whenever long-period progressive waves pass through the surf zone and reflect from shore. Comparison of observed and calculated long-wave phase velocity for progressive waves in the surf zone indicated they were non-dispersive. Amplitudes of long-period progressive waves decreased shoreward, in response to energy loss and redistribution. Standing waves occurred, both singularly and in groups, at irregular time intervals between sequences of progressive waves. This pattern is most likely created by non-linear interactions of the progressive wave groups. Standing wave amplitudes appear to reach a maximum within the range of breaking waves and approach nodes at the shoreline and offshore. This positioning of nodes and antinodes is in agreement with that of Suhayda (1974), but the irregular periodicity is not.

Actually, this lack of similarity in the time domain is
easily explained by the difference in incident wave condi-
tions. Suhayda's observations were made under conditions
of regular swell arriving at the coastline while ours were
made when wind-waves dominated the incident wave field.
Thus, from a mechanistic standpoint both sets of results
seem to be in complete agreement.

The long-period component, from decomposition of
synchronus 1000 second longshore current velocity time series,
ranges from 45 to 48 seconds. This periodicity greatly
exceeds that of the incident progressive long wave (15 to 18
seconds) and cannot be reasonably compared with that of the
standing wave. It is qualitatively interesting to note
that irregular periodicities in the long-period component
of longshore current velocity have been observed during
earlier analyses of this data (Meadows, 1977). Likewise
these long-period variations have been postulated to be
related to non-linear wave interactions which result in
irregular standing wave patterns. The correlation between
standing wave period non-linearities and non-linearities in
the long-period component of longshore current velocity
strongly supports a driving mechanism which arises from
complex surf beats. A recent paper "Long-Period Surf Zone
Motions" (Meadows and Wood, in press in JGR Green) discusses
these relationships in detail.

Existing methods for the prediction of longshore current
velocity distribution across the surf zone utilize, either a

monochromatic, incident wave field and a horizontal mixing coefficient (Bowen, 1969; Thornton, 1969; Longuet-Higgins, 1970 a and b) or a probabilistic, incident wave field and differential breaking (Collins, 1972) to approximate velocity distributions. There is no expectation of longshore current flow, outside the break point, when a monochromatic wave assumption is used for prediction. Therefore, Bowen (1969), Thornton (1969) and Longuet-Higgins (1970 a and b) introduced various forms of mixing coefficients in order to obtain better matches between observed and predicted longshore current distributions. Collins (1972) assumed that a probabilistic incident wave field was much more representative of observed field conditions and then utilized this assumption to develop a method for predicting longshore current distributions across the surf zone. Differential wave breaking, which results from an ensemble of incident wave heights, creates a well mixed outer region of the surf zone, without having to apply a mixing coefficient. Collins (1972) argued, quite reasonably from physical principles, that differential wave breaking provided the mixing mechanism for the outer surf zone.

Comparisons have been made between observed, single maximum, horizontal longshore current profiles and profiles predicted from the semi-theoretical work of Longuet-Higgins (1970) and Collins (1972). Additional comparisons with predicted profiles of Bowen (1969), Thornton (1969) and James (1974) have also been carried out. An extensive discussion of this work is presented in Meadows (1978).

An extensive evaluation has been made of Longuet-
Higgins (1970) formulation for the prediction of longshore
horizontal current velocity profiles. A matching of
predicted profiles, generated from Longuet-Higgins semi-
theoretical formulation, with observed profiles from this
study has been carried out by manipulating the range of
constants applied to his formulation. These manipulations
involved the amplitude to depth ratio (α), the deep water
to shallow water transformation coefficient (B), the friction
coefficient (C), the dimensionless scaling coefficient (N)
and the horizontal eddy viscosity (μ). Comparisons between
predicted and observed profiles for the range of observed
parameters were not good. The magnitude of the predicted
velocities was too small and the shape of the predicted
profile was not similar to the observed. Specifically, the
predicted outer "mixed" region of the current profile trun-
cated too abruptly. Variation of the friction coefficient
allowed the predicted and observed profiles to be matched at
the point of maximum velocity, but the shape distortions
became greater. The physical significance of this type of
"matching" is not at all clear or necessarily reasonable.
In fact it may well be an exercise in futility if the problem
lies in the basic formulation of Longuet-Higgins (1970).

Comparisons between Collins (1972) longshore current
velocity predictions and direct field observations show
that the shapes of predicted velocity distributions are much
broader than actually observed. This result is somewhat
anticipated because Wood (1974) has shown that the Rayleigh

distribution assumed by Collins (1972) is not representative
of the observed incident wave field in the surf zone.
Specifically, the tail of the distribution, composed of
high incident waves, is compressed so that a truncated
Gaussian distribution results.

A truncated Gaussian distribution was substituted for
the Rayleigh distribution assumed by Collins (1972) and a
new set of predicted longshore current distributions were
generated. These predicted distributions had shapes which
compared favorably with observed distributions. However,
the magnitude of these predicted distributions was greater
than observed.

One of the primary reasons for this lack of agreement
is the unrealistic neglect of turbulent dissipation of energy,
due to breaking. This neglect is surprising since most inves-
tigators readily acknowledge its importance. What seems to
have been assumed in derivations of existing longshore
velocity formulations is that any effects of turbulent decay
are linear from the break-point shoreward. While this assump-
tion provides tractable algebra it is not supported by field
observations (Horikawa and Kuo, 1966; Wood, 1972; Suhayda
and Pettigrew, 1977).

A semi-theoretical formulation for calculating longshore
current velocity across the surf zone has been derived using
turbulent decay of breaking wave energy to balance incident
wave energy flux. Basic assumptions to this formulation are

that the: wave field is two-dimensional, individual waves
behave as a second order solitary wave, bottom is essentially
horizontal in the range of decay, and wave height decay due
to breaking is an exponential function of distance from break
point. The resulting formulation for mean velocity ($\bar{V}$) at
any point x in the surf zone is

$$\bar{V} = 1.22\ e^{-0.02x}\ \sin\theta$$

where θ is the wave angle of incidence at x. Initial compari-
sons between velocities calculated using this formulation
and observed longshore current velocities showed considerably
better agreement than was achieved using existing formulations.
Maximum error in the calculated velocities occurs in the
immediate region around the break-point. Much of this error
can be explained by the use of single-valued means for the
input parameters. Computations and comparisons currently
being carried out utilize distributional properties of the
input parameters and should yield better agreement with the
new formulation. A paper "Horizontal Distribution of Longshore
Current Velocity" (Wood and Meadows, in preparation) describes
this work in detail.

Vertical distribution of longshore current velocity has
always been assumed to be uniform from the bottom to the
free surface. This assumption has been applied to all
existing theoretical and empirical formulations for predicting
longshore current velocity. Consequently, surface longshore
current velocity distribution has been used to approximate

the velocity distribution at any level throughout the
vertical, exclusive of the near bottom boundary layer.

Measurements of vertical longshore velocity distribution
at four points across the surf zone were made during the fall,
1976 field experiment. A similar set of measurements had
been made during the 1974 field experiment, at three locations
within the surf zone. These earlier measurements were closely
spaced near the breaker zone. Analysis of both sets of data
shows that the vertical distribution of longshore current
velocity is relatively uniform with depth. However, there
is a consistent reduction of velocity in the lower third
of the vertical profile. This velocity reduction occurs
in the same depth range at which Wood (1970) measured
extremely reduced horizontal particle velocities in trans-
forming breaking waves.

A series of overlapping 30 second time averages of the
longshore velocity at each level in the vertical profile
shows that the profile is unsteady. However, the long-period
variations (30 to 90 seconds) in the mean velocity profile
are in phase throughout the column. Thus, the shape of the
vertical profile remains constant, but the absolute magnitude
of the velocity at each level fluctuates in a periodic manner.

Future work should be pursued to establish a method for
predicting the vertical velocity distribution of longshore
current. Clearly, the existing assumption of steady, verti-
cally uniform currents is oversimplified and may lead to

erroneous conclusions when it is applied to calculation of
bed shear stress and resulting sediment transport. An
adequate solution to this problem can only be obtained
through detailed laboratory measurements.

Our work has provided the first detailed observations
on horizontal and vertical structure in longshore currents
and has raised interesting questions on temporal variations
in current velocity. Although a number of papers and reports
have been prepared on this work there is still a great deal
more analysis which can be done on this data field. It is
anticipated that at least two more papers will be prepared
from these results within the next 18 months.

LABORATORY EXPERIMENTS ON BREAKING WAVES

Three separate laboratory experiments have been conducted on breaking wave height decay over a horizontal bottom. The primary purpose of these laboratory experiments was to verify the scale lengths which are predicted from application of isotropic turbulent kinetic energy dissipation theory to second order solitary wave theory. Specifically, an attempt was made to establish the interrelationship between internal "vortex" dimensions and the rate of wave height decay with respect to horizontal distance from breaking.

Conceptualization of these experiments is based upon the recognition that energy is released into the surf zone in a turbulent state under most breaking wave conditions. This physical state is, however, a difficult one to model appropriately without developing a proper set of mathematical relationships between the energy transport mechanism (waves and associated particle motions) and the energy dissipation mechanisms (internal turbulence). Field measurements tend to sample surface wave characteristics and in a limited number of cases, internal flow fields. Through the application of linear wave theory, semi-theoretical tuning of wave height decay prediction equations has been accomplished. Extension of these theories to interpretation of internal flow fields is not acceptable because none of them have been

formulated within the context of turbulent flow. Use of mean values from field measurements of surf zone flows to verify these physically unrealistic internal flows create two additional problems. First, it perpetuates a conceptualization of surf zone dynamics which is quite incorrect. Second, it minimizes the wealth of information recorded by field sensors.

Development of a more appropriate theoretical approach is proceeding along the following lines: first it is assumed that isotropic or axisymmetric turbulent flow can, to a first approximation, be applied to conditions of wave breaking; second it is assumed that second order solitary wave theory provides a reasonable description of wave form and behavior up to breaking; third waves are considered at normal incidence (a restriction which can be relaxed later) and in only two dimensions; fourth only dissipation of kinetic energy due to turbulence is considered (energy transfer from mean motion through turbulent shear stresses and work done by viscous shear stresses are initially being neglected). A comment on this last simplifying assumption; for the initial case, $\partial \bar{U}j/\partial x_i$ in the energy transfer term is assumed to have a constant negative value, thus kinetic energy of turbulence decreases in a regular manner across the surf zone. In the future it would be of interest to consider this term and then allow it to become positive within the surf zone in order to evaluate its contribution to reforming of breaking waves.

Three separate laboratory experiments have been conducted on breaking wave height decay in shallow water. A total of twenty-nine complete wave series (each consisting of eight individual wave decay sequences) were measured during these experiments. Wave heights at breaking ranged from 10cm to 26cm and water depths were held constant at 16cm, 20cm and 24cm in each of the three experiments respectively. This range of conditions produced a full spectrum of wave types, from unbroken solitary to fully turbulent plunging breakers.

One of the most striking results from these experiments was the identification of two step like transitions in wave height decay of fully turbulent plunging breakers. At breaking a plunging breaker was observed to undergo a rapid loss of wave height (30 to 40 percent of maximum wave height) over a very short distance. It then traveled with relatively constant height, while still visibly turbulent, for considerable distance until it underwent a "jump" like transition to a solitary wave. The first of these transitions was dependent on initial breaking height, but the second was independent of initial height. The first of these transitions is similar to that observed in earlier field experiments on wave transformations (Wood, 1970, 1972). The second of these transitions would not be anticipated in the field because of rebuilding and secondary breaking. However, it is a significant result because it strongly supports the argument that the dynamics of a plunging breaking wave are "well behaved".

Analysis is completed on wave height decay data for breaking waves on a horizontal bottom. A full range of breaker types (spilling to plunging) are represented in these data. Breaker types are determined from both free surface time history profiles and photographic records of the wave, which eliminates the ambiguities inherent in using only free surface profiles. Figure 1 shows a set of wave height decay results for "G" settings of 18 (gently spilling) to 30 (fully plunging). These data show increasing non-linear decay with respect to "G" in the region immediately following breaking. Physically this means that as wave energy density at breaking increases, the intensity of post breaking dissipation increases. This physical behavior of decaying waves after breaking is not explained by existing frictionally dominated decay expressions. In fact the most commonly used relation for post breaking wave height decay $\alpha = H/2d$ is inconsistent with these data. These laboratory results are, however, in agreement with field results from earlier work under this contract (Wood, 1970, 1972). Most importantly these results provide a quantitative framework for development of appropriate nearshore energy (momentum) models. For example much of the difficulty in the longshore current model of Longuet-Higgins (1970) results from his use of the aforementioned linear decay criterion.

These wave height decay results were used to evaluate a numerical model of wave energy dissipation in a turbulent flow field. The primary objectives of this evaluation were
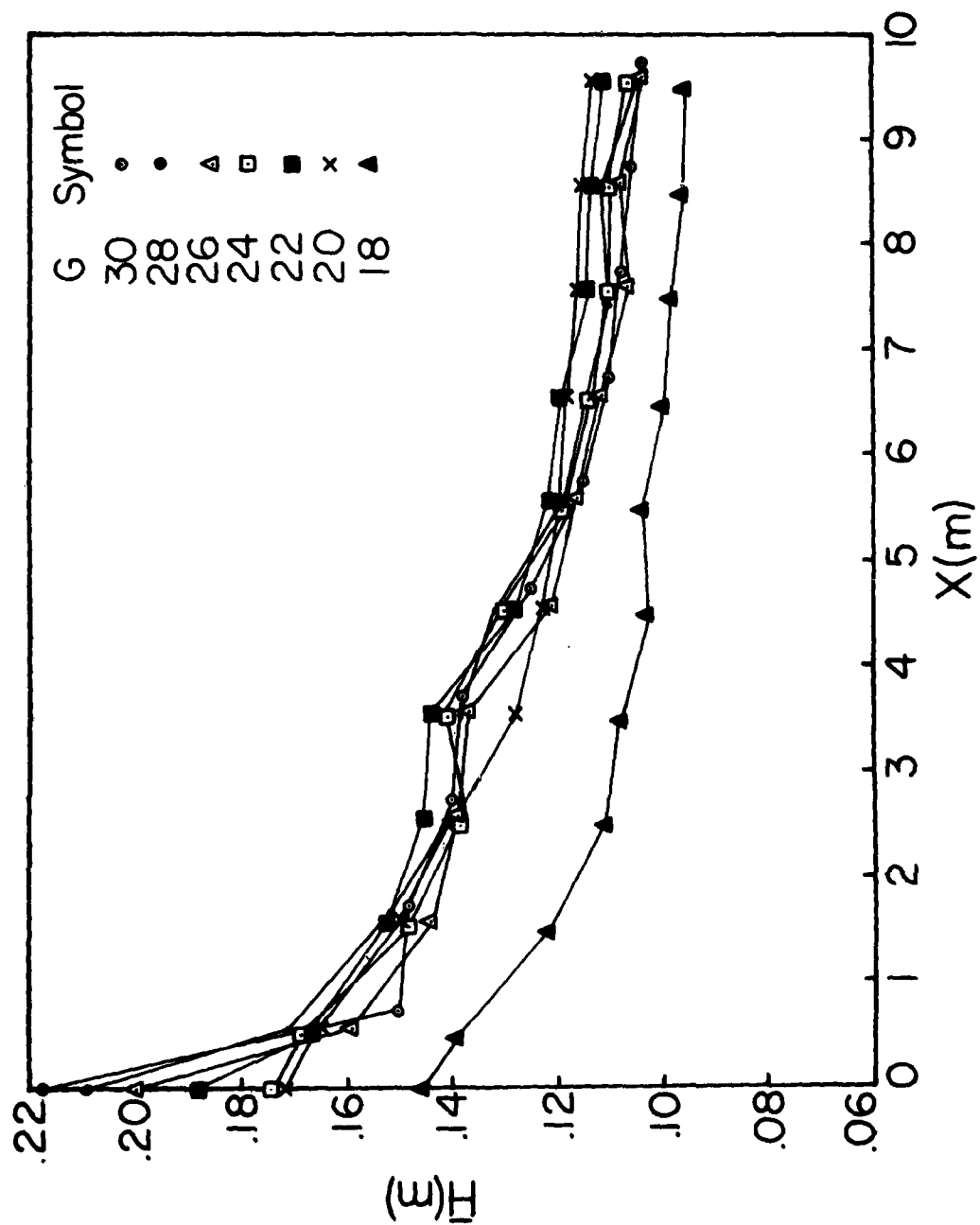
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Figure 1. Wave height decay with distance from break point.

to determine whether the turbulent decay coefficient (β)
was a constant and to calculate its magnitude. β is the only
model parameter which is not assumed to be directly dependent
on initial wave characteristics. Therefore, the initial
conditions for each experimental data set were used as input
to the model and β was varied until a "best" fit was achieved
between the model decay curve and the observed data.

Results of this evaluation show that β is not a constant,
as suggested by Horikawa and Kuo (1966). β varies directly
as a function of wave height and has a range of 0.2 to 1.5.
This range of values for β is similar to that obtained in
earlier Lake Michigan field studies conducted under this
contract (Wood, 1970, 1972). These results contradict the
original conclusion of Horikawa and Kuo (1966) that β is a
constant value between 4 and 5 for laboratory scale decay
and near 1 for field scale decay. Clearly, laboratory results
from this study support field results of Wood (1970, 1972)
and Ijima (1958). The reason for Horikawa and Kuo's (1966)
high β value from laboratory data is not obvious because
their scale lengths were comparable to those used in this
set of experiments.

Most important in this set of results is the agreement
between field and laboratory values for turbulent decay
coefficients. It is equally important that the variation of
β was systematic and dependent upon the same parameters in
both field and laboratory experiments.

A paper "Breaking Wave Decay in the Surf Zone" (Price, 1979) presents a detailed discussion of these results. A second paper "Wave Height Decay Due to Breaking" (Wood, 1981) discusses the implications for turbulent decay models in the surf zone.

This laboratory work has been considerably more revealing than originally anticipated. The agreement achieved between laboratory and field scales for β resolves a long standing problem in the turbulence dynamics of wave height decay.

Recently hot film anemometer measurements of horizontal particle velocities have been made simultaneously with collimated light motion pictures of transforming breaking waves. Resolution of internal motions in breaking waves and their associated flow fields, from motion picture records, is being greatly enhanced through the use of a computer interactive film analyzer "Galetea". It is premature to comment on these results except to point out that measurements of free surface deformation and internal particle accelerations are being made on a scale previously unattainable from laboratory data.

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APPENDIX A

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CONTRACT N00014-75-C-0716

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Final Report	2. GOVT ACCESSION NO. AD-A093 452	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Application of Short-Crested Wave Theory in the Design of Three-Dimensional Coastal Hydrodynamic Models		5. TYPE OF REPORT & PERIOD COVERED Final Report May, 1975-Sept. 1980
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) William L. Wood		8. CONTRACT OR GRANT NUMBER(s) N 00014-75-C-0716
9. PERFORMING ORGANIZATION NAME AND ADDRESS Great Lakes Coastal Research Laboratory Dept of Geosciences, Purdue Univ. West Lafayette, IN 47907		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NR 388-089
11. CONTROLLING OFFICE NAME AND ADDRESS ONR, Coastal Sciences Program Code 462 Arlington, VA 22217		12. REPORT DATE September 1980
		13. NUMBER OF PAGES 26
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Office of Naval Research Resident Rep. The Ohio State Univ. Research Center Columbus, OH 43212		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Distribution of this document is unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Short-crested waves; longshore currents; breaking wave height decay

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In spring 1973 a series of field experiments was initiated to investigate the three dimensional structure of a coastal hydrodynamic system. These field investigations supported the concept that short-crested wave theory is applicable to modeling of incident wind-wave transformations from offshore to the outer surf zone. Application of short-crested wave theory to the design of coastal hydrodynamic models was also considered

appropriate because of the theories inherent three dimensional structure. Concurrent with this work two field experiments were conducted in 1974 and 1976 to measure vertical and horizontal distribution of longshore current velocity and to monitor temporal variations in current velocity at a point. In fall 1978 a series of experimental laboratory investigations was initiated to make precise measurements, at close spatial intervals, of wave height decay after breaking. These experiments were carried out to determine a wave height decay expression based upon the assumption that an appropriate physical conceptualization of wave energy dissipation after breaking must consider turbulence dominant to bottom friction. This report presents a detailed summary of these investigations and their results.